Chapter 2
Thermal Spray Fundamentals

2-1. Introduction

This chapter introduces the engineer to the fundamental principles of thermal spray, coating types and characteristics, thermal spraying processes, and thermal spray uses.

2-2. General Description of Thermal Spraying

Thermal spraying is a group of processes wherein a feedstock material is heated and propelled as individual particles or droplets onto a surface. The thermal spray gun generates the necessary heat by using combustible gases or an electric arc. As the materials are heated, they are changed to a plastic or molten state and are confined and accelerated by a compressed gas stream to the substrate. The particles strike the substrate, flatten, and form thin platelets (splats) that conform and adhere to the irregularities of the prepared substrate and to each other. As the sprayed particles impinge upon the surface, they cool and build up, splat by splat, into a laminar structure forming the thermal spray coating. Figure 2-1 illustrates a typical coating cross section of the laminar structure of oxides and inclusions. The coating that is formed is not homogenous and typically contains a certain degree of porosity, and, in the case of sprayed metals, the coating will contain oxides of the metal. Feedstock material may be any substance that can be melted, including metals, metallic compounds, cements, oxides, glasses, and polymers. Feedstock materials can be sprayed as powders, wires, or rods. The bond between the substrate and the coating may be mechanical, chemical, or metallurgical or a combination of these. The properties of the applied coating are dependent on the feedstock material, the thermal spray process and application parameters, and posttreatment of the applied coating.

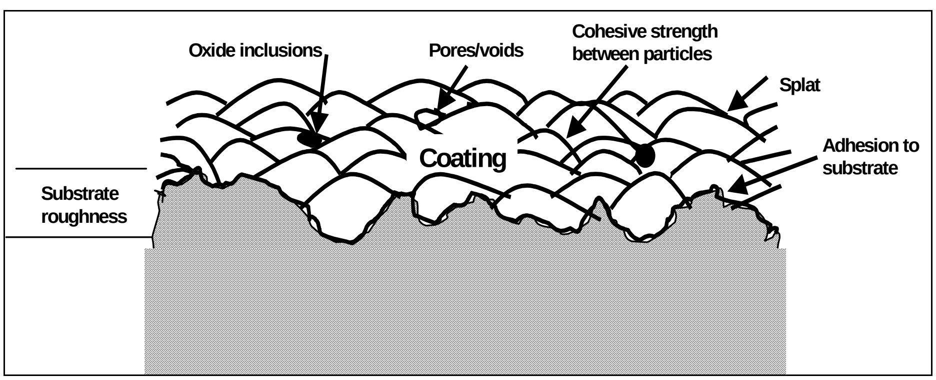

Figure 2-1 Typical cross section of a thermal spray coating

2-3. Characteristics of Thermal Spray Coatings

a. Hardness, density, and porosity. Thermal spray coatings are often used because of their high degree of hardness relative to paint coatings. Their hardness and erosion resistance make them especially valuable in high-wear applications. The hardness and density of thermal spray coatings are typically lower than for the feedstock material from which the coatings were formed. In the case of thermal spray metallic coatings, the hardness and density of the coating depend on the thermal spray material, type of thermal spray equipment, and the spray parameters. In general, the higher the particle velocity, the harder and denser the coating. Particle velocities for different thermal spray processes in descending order are detonation, high-velocity oxygen flame (HVOF), arc plasma, arc wire, and flame spray. Hardness and density may also depend on particle temperature and the type of atomization gas used. The porosity of the coating depends also on the thermal spray process, application parameters, and thermal spray material.

b. Corrosion resistance. Metallic thermal spray coatings may be either anodic or cathodic to the underlying metal substrate. Because corrosion occurs at the anode, anodic coatings will corrode in corrosive environments and the cathode will not. Anticorrosive coating systems are generally designed such that the coating material is anodic to the substrate metal. Anodic coatings will corrode or sacrifice to protect the substrate. In some cases, the corrosion resistance of the thermal spray material itself is important. For very high temperature applications and for chemical exposures, the thermal spray coating must be very corrosion resistant. For such applications, the coating provides a corrosion resistant barrier to protect the substrate. For a more complete discussion of corrosion theory please refer to Chapter 2 of EM 1110-2-3400.

c. Adhesion. Thermal spray coatings may have very high adhesion. Special coatings, used for wear resistance, that are applied by thermal spray processes with very high particle velocity can have tensile adhesions of greater than 34,000 kPa (5000 psi) as measured by ASTM C633 “Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings.” Most coatings used for infrastructure applications have adhesion values comparable to paint coatings. Typical field- and shop-applied zinc, aluminum, and zinc-aluminum alloy coatings will have adhesion ranging from 5440 to 13,600 kPa (800 to 2000 psi) as measured by ASTM D4541 “Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers.”

2-4. Types of Thermal Spray Coatings

a. Corrosion resistant zinc, aluminum, and zinc-aluminum alloy coatings. Zinc, aluminum, and zinc-aluminum alloy coatings are important anticorrosive coatings because they are anodic to steel. In other words, they corrode preferentially to steel, acting as sacrificial coatings preventing the corrosion of the underlying steel substrate. Zinc is a much more active metal in this respect than aluminum. On the other hand, aluminum coatings are harder, have better adhesion, and form a protective oxide layer that prevents self-corrosion. Alloys of the two metals have properties somewhere in between, depending on the ratio of zinc to aluminum. An 85-15 (percent by weight) alloy of zinc and aluminum is a widely used thermal spray coating material because it is thought to have the best combination of attributes from both metals.

b. Polymer coatings. Thermal spray polymer or plastic coatings have been developed for infrastructure applications. Thermal spray polymers are thermoplastic powders applied by flame or plasma spray. The polymer must have a melt temperature that is conducive to thermal spray. In addition, the polymer must not polymerize, degrade, or char in the flame. Thermal spray plastics do not contain volatile organic compounds and thus are compliant for use in areas with air pollution regulations. Thermal spray polymer coatings have been used to coat steel under very cold atmospheric conditions when painting was not practical. Research has been conducted on the use of recycled plastics for polymer flame spray, and these products show some potential. There appears to be a growing interest in polymer flame spray for infrastructure applications. The Society for Protective Coatings is developing a specification for polymer flame spray, and several vendors offer equipment and polymer feedstocks.

c. Other thermal spray coatings. Other thermal spray coating materials are used for special applications. Special metal alloy coatings are commonly used for hardfacing items such as wear surfaces of farm equipment, jet engine components, and machine tools. Ferrous metal alloys are often used for restoration or redimensioning of worn equipment. Special ferrous alloys are sometimes used for high-temperature corrosion resistance. Inert ceramic coatings have been used on medical prosthetic devices and implants such as joint replacements. Conductive metal coatings are used for shielding sensitive electronic equipment against electric and magnetic fields. Ceramic coatings have also been used to produce very low-friction surfaces on near net shape components. These and other applications make thermal spray coatings a diverse industry.

2-5. Thermal Spray Processes

Thermal spray processes may be categorized as either combustion or electric processes. Combustion processes include flame spraying, HVOC spraying, and detonation flame spraying. Electric processes include arc spraying and plasma spraying.

a. Combustion processes.

(1) Flame spraying. The oldest form of thermal spray, flame spraying, may be used to apply a wide variety of feedstock materials including metal wires, ceramic rods, and metallic and nonmetallic powders. In flame spraying, the feedstock material is fed continuously to the tip of the spray gun where it is melted in a fuel gas flame and propelled to the substrate in a stream of atomizing gas. Common fuel gases are acetylene, propane, and methyl acetylene-propadiene. Air is typically used as the atomization gas. Oxyacetylene flames are used extensively for wire flame spraying because of the degree of control and the high temperatures offered by these gases. By gauging its appearance, the flame can be easily adjusted to be an oxidizing, neutral, or reducing flame. The lower temperature propane flame can be used for lower melting metals such as aluminum and zinc as well as polymer feedstocks. The basic components of a flame spray system include the flame spray gun, feedstock material and feeding mechanism, oxygen and fuel gases with flowmeters and pressure regulators, and an air compressor and regulator.

(a) Wire flame spraying. Wire flame spray is the flame process of greatest interest to the Corps of Engineers. CEGS-09971 allows for the application of aluminum, zinc, and zinc/aluminum alloy coatings using the flame spray method. Figure 2-2 shows a schematic of a typical flame spray system. Figure 2-3 depicts a typical wire flame spray gun. The wire flame spray gun consists of a drive unit with a motor and drive rollers for feeding the wire and a gas head with valves, gas nozzle, and air cap that control the flame and atomization air. Compared with arc spraying, wire flame spraying is generally slower and more costly because of the relatively high cost of the oxygen-fuel gas mixture compared with the cost of electricity. However, flame spraying systems, at only one-third to one-half the cost of wire arc spray systems, are significantly cheaper. Flame spray systems are field portable and may be used to apply quality metal coatings for corrosion protection.

(b) Powder flame spraying. Powder flame operates in much the same way as wire flame spray except that a powder feedstock material is used rather than wire and there is no atomizing air stream. The melted coating material is atomized and propelled to the surface in the stream of burning fuel gas. The powder is stored in either a gravity type hopper attached to the top of a spray gun or a larger air or inert gas entrainment type detached hopper. Powder flame spray guns are lighter and smaller than other types of thermal spray guns. Production rates for powder flame spray are generally less than for wire flame spray or arc spray. Particle velocities are lower for flame spray, and the applied coatings are generally less dense and not as adherent as those applied by other thermal spray methods. USACE use of powder flame spray should be limited to repair of small areas of previously applied thermal spray coatings and galvanizing. Figure 2-4 illustrates a typical combustion powder gun installation, and Figure 2-5 shows a powder gun cross section.

(2) HVOF spraying. One of the newest methods of thermal spray, HVOF, utilizes oxygen and a fuel gas at high pressure. Typical fuel gases are propane, propylene, and hydrogen. The burning gas mixture is accelerated to supersonic speeds, and a powdered feedstock is injected into the flame. The process minimizes thermal input and maximizes particle kinetic energy to produce coatings that are very

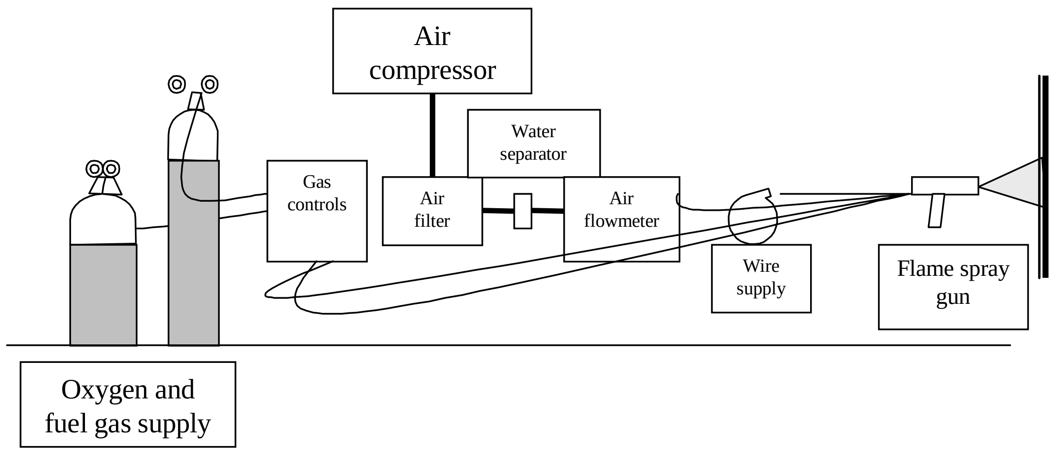

Figure 2-2. Typical flame spray system

dense, with low porosity and high bond strength. HVOF systems are field portable but are primarily used in fabrication shops. HVOF has been used extensively to apply wear resistant coatings for applications such as jet engine components. The Corps has conducted an experimental evaluation of HVOF-applied metal alloy coatings for protection against cavitation wear in hydraulic turbines.

(3) Detonation flame spraying. In detonation flame spraying, a mixture of oxygen, acetylene, and powdered feedstock material are detonated by sparks in a gun chamber several times per second. The coating material is deposited at very high velocities to produce very dense coatings. Typical applications include wear resistant ceramic coatings for high-temperature use. Detonation flame spraying can only be performed in a fabrication shop. Detonation flame spraying is not applicable for USACE projects.

b. Electric processes.

(1) Arc spraying. Arc spraying is generally the most economical thermal spray method for applying corrosion resistant metal coatings, including zinc, aluminum, and their alloys as described in CEGS-09971. Energy costs are lower and production rates are higher than they are with competing methods such as wire flame spray. Arc spraying may be used to apply electrically conductive materials including metals, alloys, and metal-metal oxide mixtures. In arc spraying, an arc between two wires is used to melt the coating material. Compressed gas, usually air, is used to atomize and propel the molten material to the substrate. The two wires are continuously fed to the gun at a uniform speed. A low voltage (18 to 40 volts) direct current (DC) power supply is used, with one wire serving as the cathode and the other as the anode. Figure 2-6 shows a typical arc spray system comprised of a DC power supply, insulated power

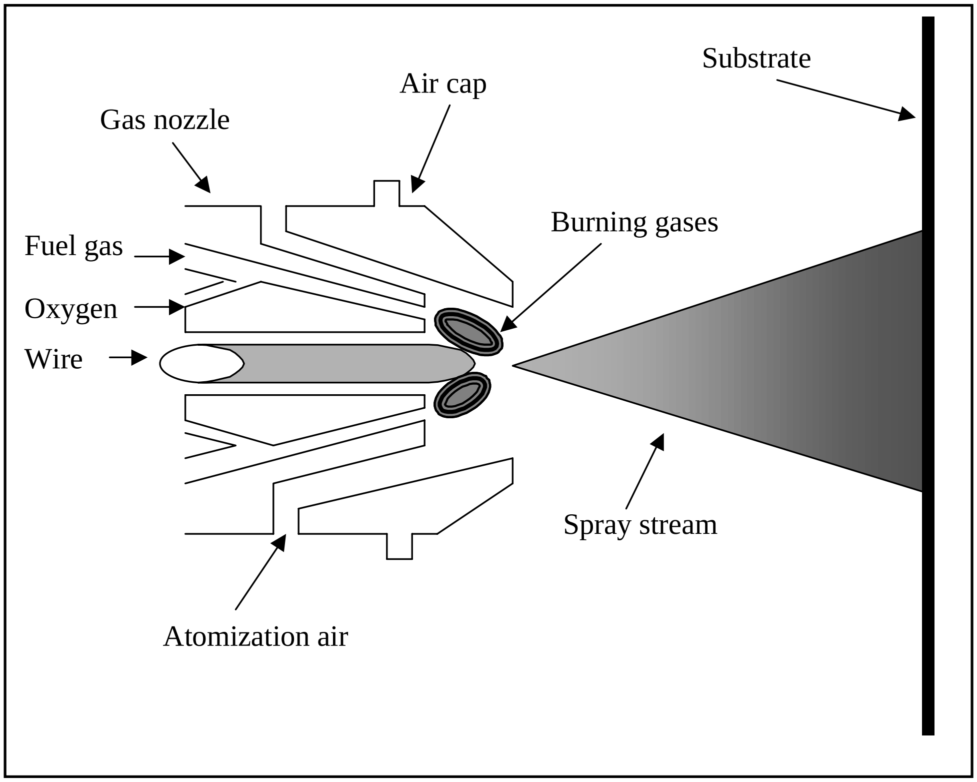

Figure 2-3. Typical flame spray gun

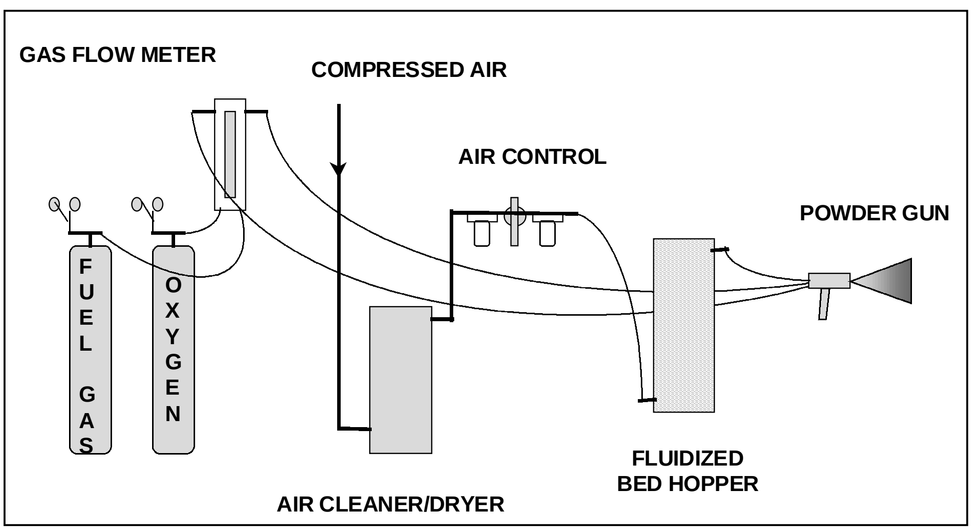

Figure 2-4. Typical combustion powder gun installation

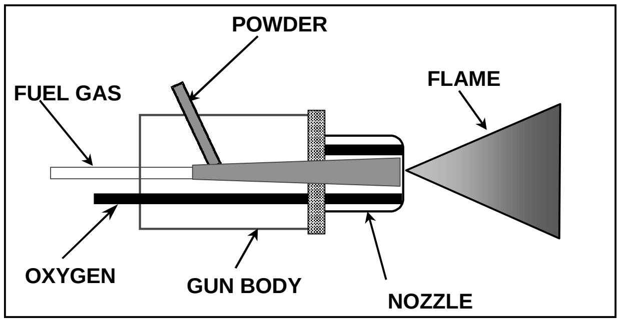

Figure 2-5. Powder gun cross section

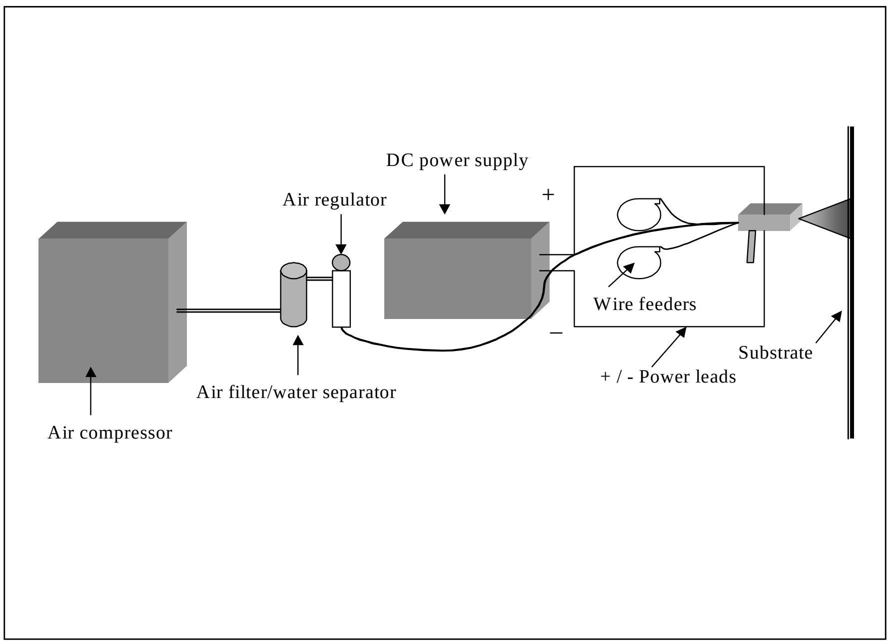

Figure 2-6. Typical two-wire arc spray system

cables, a wire feed system, a compressed-air supply, controls, and an arc spray gun. Figure 2-7 shows the components of a typical arc spray gun, including wire guides, gun housing, and gas nozzle. Coating quality and properties can be controlled by varying the atomization pressure, air nozzle shape, power, wire feed rate, traverse speed, and standoff distance. Arc sprayed coatings exhibit excellent adhesive and cohesive strength.

(2) Plasma spraying. Plasma spraying is used to apply surfacing materials that melt at very high temperatures. An arc is formed between an electrode and the spray nozzle, which acts as the second electrode. A pressurized inert gas is passed between the electrodes where it is heated to very high temperatures to form a plasma gas. Powdered feedstock material is then introduced into the heated gas where it melts and is propelled to the substrate at a high velocity. A plasma spray system consists of a power supply, gas source, gun, and powder feeding mechanism. Plasma spraying is primarily performed in fabrication shops. The process may be used to apply thermal barrier materials, such as zirconia and alumina, and wear resistant coatings such as chromium oxide.

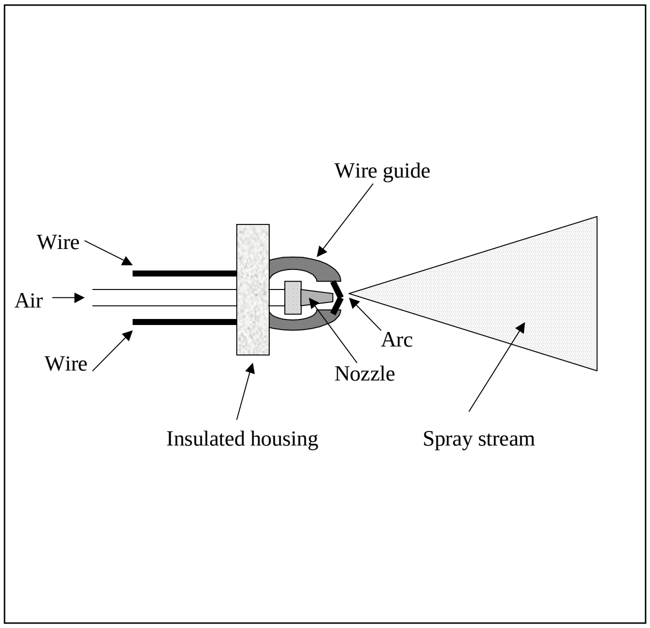

Figure 2-7. Typical two-wire arc spray gun

2-6. Thermal Spray Uses

a. Thermal spray is used for a wide variety of applications. The primary use of thermal spray coatings by the Corps is for corrosion protection. Coatings of zinc, aluminum, and their alloys are anodic to steel and iron and will prevent corrosion in a variety of service environments including atmospheric, salt- and freshwater immersion, and high-temperature applications. Coatings of aluminum are frequently used in marine environments. The U.S. Navy uses aluminum coatings for corrosion protection of many ship components. Because these materials are anodic to steel, their porosity does not impair their ability to protect the ferrous metal substrate. Zinc and zinc-aluminum alloy coatings may corrode at an accelerated rate in severe industrial atmospheres or in chemical environments where the pH is either low or high. For this reason these materials are typically sealed and painted to improve their performance.

b. Cathodic coatings such as copper-nickel alloys and stainless steels can also be used to protect mild steel from corrosion. These materials must be sealed to prevent moisture migration through the coating. These metals are particularly hard and are often used for applications requiring both corrosion and wear resistance.

c. Aluminum coatings are often used for corrosion protection at temperatures as high as 660 °C (1220 °F).

d. Thermal spray deposits containing zinc and/or copper can be used to prevent both marine and freshwater fouling. Zinc and 85-15 zinc-aluminum alloy coatings have been shown to prevent the significant attachment and fouling by zebra mussels on steel substrates. Because these coatings are long lived and prevent corrosion, their use is recommended for Corps structures. Copper and brass coatings have also been shown to be effective antifoulants but should not be used on steel due to the galvanic reaction between the two.

e. Zinc thermal spray coatings are sometimes used to prevent the corrosion of reinforcing steel imbedded in concrete. For such applications, the zinc is deposited onto the concrete and is electrically connected to the steel.

f. Thermal spray coatings are frequently used to repair surfaces subject to wear. A common application is the redimensioning of rotating shafts. Metal is sprayed onto the part as it is rotated on a lathe. The rebuilt part can then be machined to the required diameter. Similarly, thermal spray deposits can be used to recontour foundry molds or to repair holes.

g. Thermal spray coatings are also used for electrical applications. Conductive metals such as copper can be used for conductors. Ceramic materials may be used for electrical insulation. Conductive metals are also used to magnetically shield sensitive electronics.

h. Very hard and dense thermal spray deposits have been used on an experimental basis as cavitation resistant materials and in conjunction with weld overlays as a repair technique.